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A NON-ROTATING VORTICITY METER

by Michael C. McMahon and Melvin H. Snyder, Jr.

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Abstracted from the M.S. Thesis

of

Michael C. McMahon

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ABSTRACT

A non-rotating strain gage type vorticity meter has been designed for the survey of the flow field behind the delta wings being studied under NASA grant NGR 17-003-003. Calibration results for a partially instrumented meter are presented. Although these results are in the direction predicted by theory, the calibration technique needs to be improved. The concept of a non-rotating vorticity probe has been demonstrated to be feasible and further development should produce an instrument valuable for rapid mapping of extensive flow fields.

SYMBOLS

a	area, sq. ft.
A	aspect ratio of vane
b	vane span, feet
c	vane chord, inches
C_ℓ	rolling-moment coefficient $\frac{\ell}{qSb}$
C_{ℓ_p}	damping-in-roll parameter, $\frac{\partial C_\ell}{\partial\left(\frac{Pb}{2V}\right)}$
E	modulus of elasticity, p.s.i.
f_b	stress, p.s.i.
h	vane thickness, inches
I	moment of inertia, $\frac{ch^3}{12}$, $(\text{in.})^4$
K	constant of proportionality, ft.^{2}
ℓ	rolling moment, in.-lb.
M	bending moment, $\ell/2$, in.-lb.
P	rolling angular velocity, rad./sec.
$\frac{Pb}{2V}$	helix angle generated by wing tip in roll, radians
q	dynamic pressure, $\frac{\rho}{2} V^2$, lb./sq. ft.
$\bar{R}$	vector distance from reference point, ft.
s	length of path, ft.
S	vane planform area, sq. ft.
V	airspeed, ft./sec.
$\bar{V}$	velocity vector, ft./sec.
V_s	velocity component along some arbitrary path, ft./sec.

V_y	velocity component in y-direction, ft./sec.
V_z	velocity component in z-direction, ft./sec.
V_∞	freestream velocity, ft./sec.
x	coordinate, freestream direction, feet
y	coordinate, spanwise direction, feet
Y	distance from neutral axis to center of gravity, $\frac{h}{2}$, inches
z	coordinate, normal to x- and y-directions, ft.
ε	strain, inches per inch
Γ	circulation, ft.^{2}/sec.
ω	angular velocity, rad./sec.

This report briefly describes the design and calibration of a non-rotating vorticity meter. This work was carried out by Michael C. McMahon under the direction of Prof. William Wentz, the principal investigator of the project of NASA grant NGR 17-003-003. A complete description is contained in reference 1.

The purpose of this part of the project was to design an instrument which could measure the intensity of the vorticity present in wing flow fields, in particular, about slender delta wings. By measuring the vorticity distribution, the vortex cores can be located and circulation can be calculated.

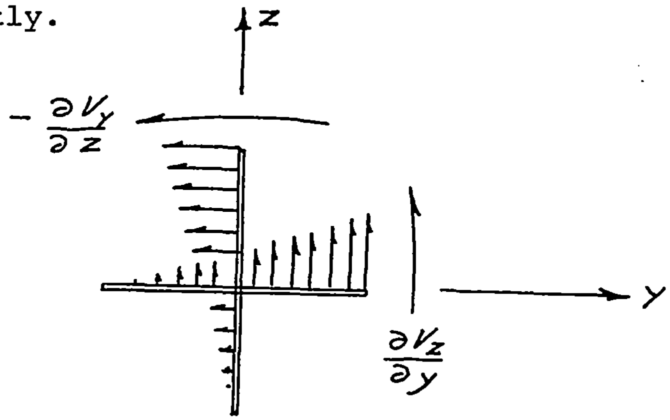
$$\text{Circulation} \equiv \Gamma \equiv \oint V_s \, ds = \oint \overline{V} \cdot d\overline{R} = \int_a (\nabla \times \overline{V}) \cdot d\overline{a}$$

This equation shows that circulation may be determined by evaluating a line integral around a path enclosing a flow field or by evaluating the distribution of vorticity $(\nabla \times \overline{V})$ over an area. In the real fluid this vorticity is distributed over finite (and often irregularly-shaped) areas.

Instruments currently being used are indirect or direct types. The indirect type of instrumentation includes the making of oil-streak or yarn-tuft pictures and the use of various types of velocity probes and miniature yaw-meters, which permit the location and mapping of the trajectory of a vortex core. Examples of direct instrumentation include vorticity meters of the types described in references 2, 3, 4, and 5. These instruments usually involve a rotating element, such as spheres, cylinders, or vanes. The result usually obtained with this type of instrument is a map of rotational speed. To obtain circulation from such a map, it would be necessary to integrate the rotation over the flow field area.

$$\Gamma = \int_a (\nabla x \overline{V}) \cdot da = \int_a 2\overline{\omega} \cdot da$$

By using two perpendicular blades, vorticity can be measured directly.



If permitted to move, one blade will tend to rotate with an angular velocity equal to $\left(-\frac{\partial V_y}{\partial z}\right)$, while the other blade will tend to rotate with an angular velocity equal to $\left(\frac{\partial V_z}{\partial y}\right)$.

If the blades are rigidly connected, the combination will tend to rotate with the average of the two angular velocities:

$$\omega_{probe} = \frac{1}{2}(\omega_1 + \omega_2) = \frac{1}{2}\left(\frac{\partial V_z}{\partial y} - \frac{\partial V_y}{\partial z}\right)$$

The term in parentheses is the expression for $\nabla x \overline{V}$ in two-dimensional form. Thus, if the probe is aligned with the vortex,

$$\overline{\omega}_{probe} = \frac{1}{2}(\nabla x \overline{V}) \quad . \tag{1}$$

In order for this statement to be strictly correct, the dimensions of the probe must be vanishingly small so that the probe responds to ω at a point. This end is achieved by making the blade span small with respect to the core of the vortex system being measured. Reference 2 shows that for a ratio of probe span to vortex span of .1 the error is negligible.

Equation (1) is the basis for the design of the rotating type meters. Such probes have been used successfully on experimental studies of trailing vortex systems associated with high aspect ratio wings. The calibration curves of one of these probes (Fig. 1) show a significant effect of free stream velocity on the probe calibration. This velocity sensitivity produces no problem if the probe is used in a flow field of nearly constant velocity. Many applications, however, are not constant velocity fields (e.g., velocity maps from a typical delta wing (Ref. 6) show that the local velocity varies from one-half to twice the free stream along a plane perpendicular to the wing surface). Since local velocity variations are not normally known in advance, it would be desirable to have a probe which was insensitive to local velocity.

A second problem of rotating devices is friction. It was found that after several hours of operation, these devices require additional lubrication and, therefore, a recalibration of the probe.

It was felt that it would be desirable to design a non-rotating vorticity meter to eliminate the friction problem and to attempt to obtain a probe which would be independent of velocity parallel to the probe axis.

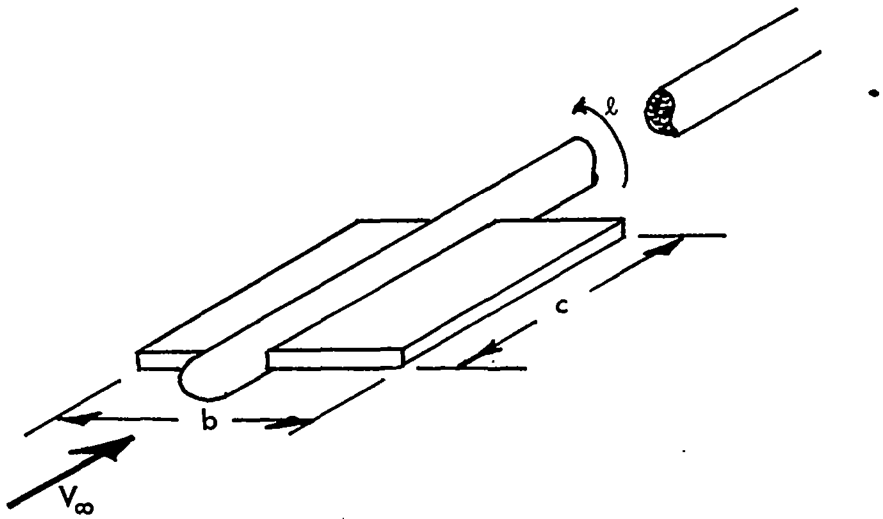
The proposed probe, as shown in figure 2, is one which measures torque on fixed blades rather than measuring the rotational speed of moving blades. The torque is sensed by the use of strain gages mounted on the blades of the probe. Measurements can be obtained directly using conventional balancing bridges.

Since the flow field being measured will be rotational with respect to the fixed vorticity probe, the blades may be treated as wings in rolling motion. The torque experienced by a fixed blade in a rotational flow field may be calculated using the damping-in-roll parameter, C_{ℓ_p}, which expresses the resistance of a wing to rolling. The angle of attack due to rolling velocity P varies linearly across the span from $\frac{Pb}{2V}$ at the tip to zero at the center span position.

The blades are treated as wings with a small aspect ratio. A plot showing the variation of damping-in-roll (at zero lift for a flat-plate airfoil wing) with aspect ratio is shown in figure 3 from reference 7. For aspect ratios of one or less the following equation was assumed valid:

$$C_{\ell_p} = \frac{\pi}{32} A$$

The following damping-in-roll analysis was made using this estimate.



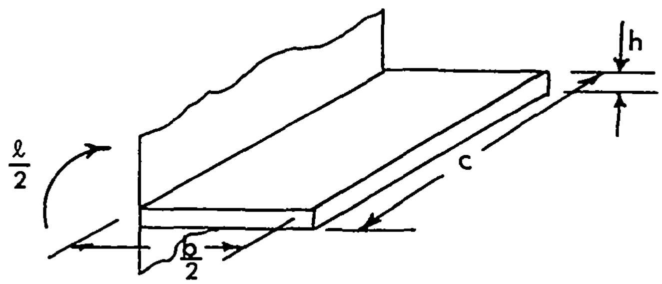
The rolling moment is $\ell = qSbC_\ell$,

$$\text{where } \frac{dC_\ell}{d\left(\frac{Pb}{2V_\infty}\right)} = C_{\ell_p} = -\frac{\pi A}{32} ;$$

$$C_\ell = -\frac{\pi A}{32}\frac{Pb}{2V_\infty} .$$

Then, $\ell = \frac{\pi}{32} A \frac{Pb}{2V_\infty} qSb$.

The maximum bending fiber stress is given by $f_b = \frac{MY}{I}$, where $M = \frac{\ell}{2}$, since ℓ is the moment due to two blades.

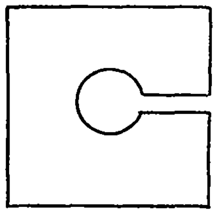


$$I = \frac{ch^3}{12}$$

is the moment of inertia for a rectangular beam and the distance from the neutral axis is $Y = \frac{h}{2}$.

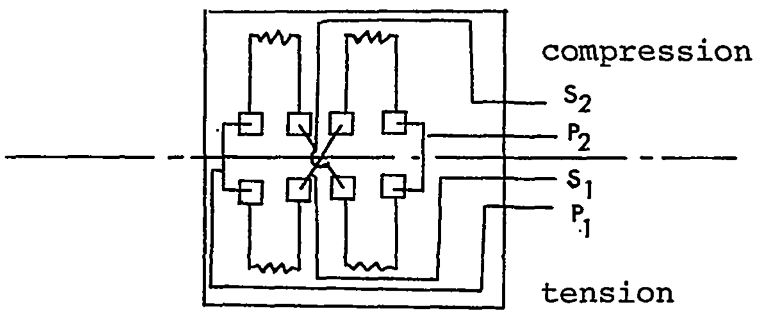
The maximum strain due to bending is $\varepsilon = \frac{f_b}{E}$.

The mounting shaft was made of .375 in. aircraft steel tubing having an inside diameter of .120 in. The blades were made of steel shim stock .005 in. thick. A paper cutter was used to cut the blades into one-inch squares with a slit in the middle so that when joined together they formed the

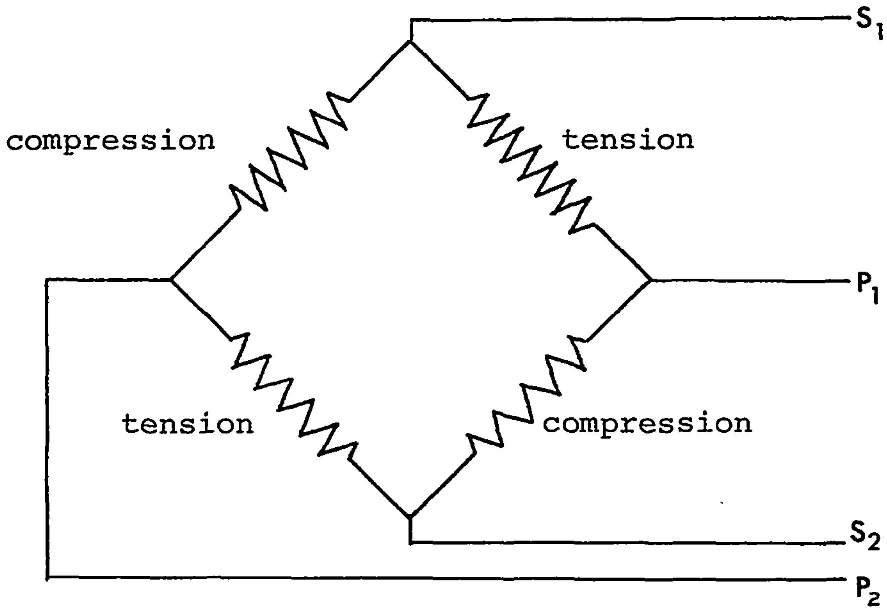


four blades of the probe. Using a paper punch, a hole was punched in the center of the blade to provide clearance for wiring the strain gage bridge. The strain gages were mounted on both sides of the blade. Gages used are C6 1x1-M20, Budd Instrument Co. gages having a gage length of .02 in. and a gage factor of 2.01.

The strain gage bridge was connected as shown.



The full bridge was connected as shown.



$$\varepsilon = \frac{f_b}{E}$$

Substituting the quantities above,

$$\varepsilon = \frac{1}{2} \frac{6}{ch^2} \frac{\pi}{32} A \frac{Pb}{2V_\infty} qSb \frac{1}{E} ,$$

which is the strain due to the rolling moment. For a rectangular planform, this equation may be written in the following forms:

$$\varepsilon = (\text{const.}) \left(\frac{b^4}{ch^2}\right)\left(\frac{qP}{V_\infty}\right)\left(\frac{1}{E}\right)$$

$$\varepsilon \propto \left(\frac{1}{h^2}\right)\left(V^2\right)\left(\frac{1}{E}\right)$$

In this form, it can be seen that the stress in the vanes is a function of the thickness and material of the vanes and the velocity of the fluid in which the probe operates.

For an aspect ratio of one, and blades made of 1 in. by 1 in. steel shim stock .005 in. thick, the strain is calculated to be $\varepsilon = .124 \quad P \frac{q}{V} \, x10^{-6}$ in/in . From an analysis of the velocity maps from reference 6, it was determined that the rolling angular velocity varied from 40 to 200 rad/sec at a tunnel dynamic pressure of 40 psf. The strain was calculated to be $\varepsilon = 2.71x10^{-6}$ in/in , which is within the range of measurement with normal strain gage equipment.

This analysis indicates that this type of vorticity meter design is feasible and that it should be possible to calibrate the probe. It also indicates that, although the use of a non-rotating element will eliminate friction, the sensitivity to local velocity is not eliminated.

The probe was designed so that it could be housed in a gimbal-type apparatus (Fig. 4) so that it could be positioned parallel with the local stream. Figure 5 shows the entire assembly.

The probe calibration was performed by placing it in a uniform flow field parallel with the free stream. The probe was then spun at various speeds. To obtain strain gage readings from the rotating probe, it was necessary to fit the shaft with slip rings, brushes and a drive motor. Only one vane was instrumented for initial calibration purposes. The results of the static loading and of the dynamic calibration are shown in figures 6 and 7.

Figure 6 indicates the linear behavior of the assembly. Figure 7 shows the strain gage indication as a function of rotational speed. It will be noted that there is considerable effect of free-stream velocity on the strain indication. The variation with rotational speed, at a given dynamic pressure, is fairly linear, as expected.

Considerable difficulty was experienced with the slip ring and brush assemblies during the calibration. Thus, Figure 7 should be not considered as a calibration curve, but rather as an indication of the type of calibration which is possible.

Thus far, the probe has been used in only one wind tunnel test, that shown in Figure 5-b. The position of the vortex filament was obtained within one-tenth of an inch. Figure 8 shows the position of the center of the vortex core located on a map of the velocity components in the x-z plane. The velocity map was obtained using the velocity field probe described in reference 6. The location of the vortex core center using the velocity map is less accurate than the location obtained from the vortex probe.

It is felt that the work to date has yielded the following results:

1. It has been shown that the design and fabrication of a non-rotating vorticity meter is feasible.

2. The damping-in-roll theory for a low aspect ratio wing proved useful in blade design.

3. As shown in theoretical design and experimental data, the probe proved sensitive to local velocities necessitating additional instrumentation to sense the local velocity.

4. The problem of passing strain gage signals through slip rings and brushes is practicably insurmountable. Complete calibration should be performed using a known rotational field of flow instead of rotating the instrument.

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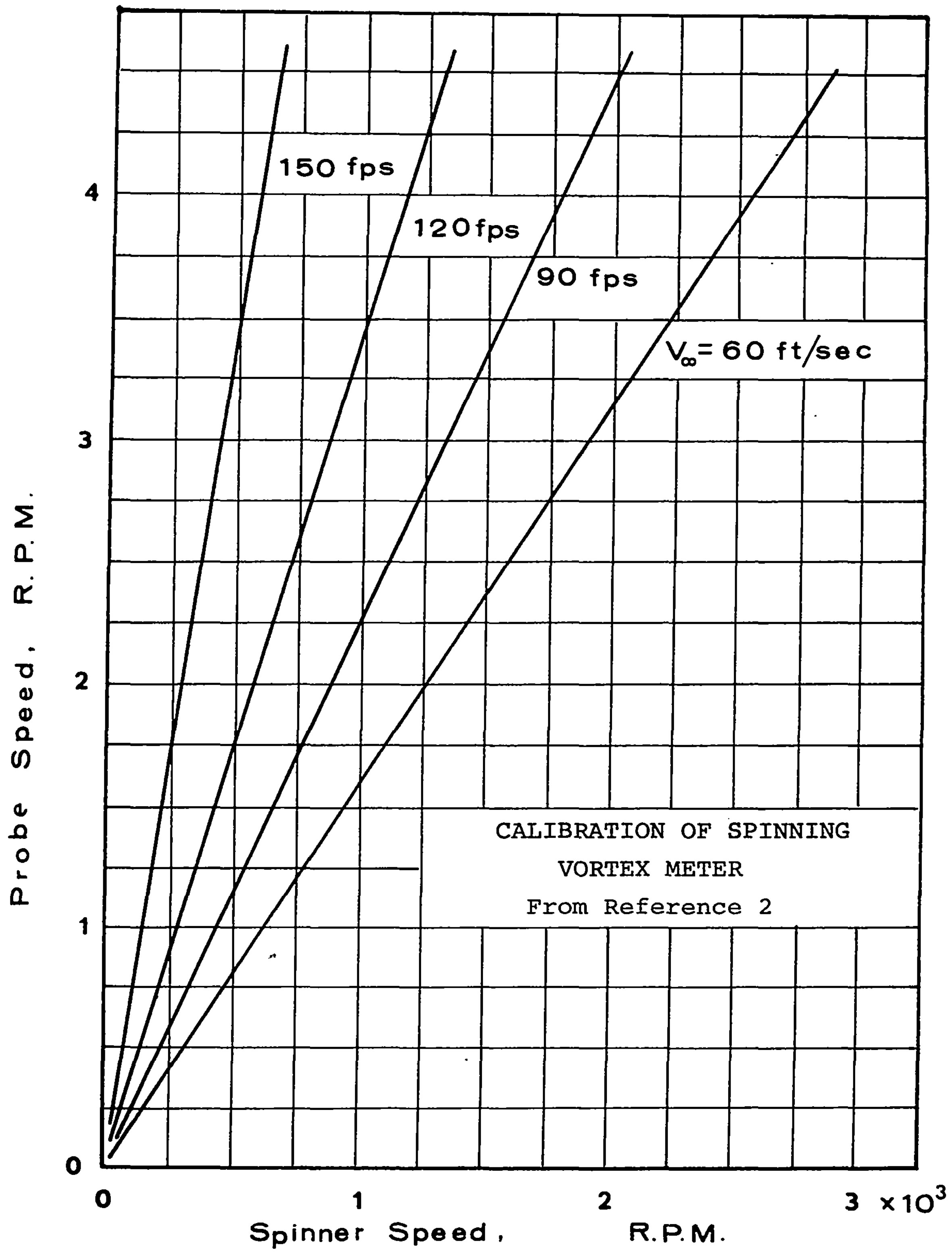

150 fps
120fps
90 fps
V_∞= 60 ft/sec
CALIBRATION OF SPINNING
VORTEX METER
From Reference 2
Probe Speed, R.P.M.
0
1
2
3
4
0
1
2
3 ×10³
Spinner Speed, R.P.M.

Figure 1

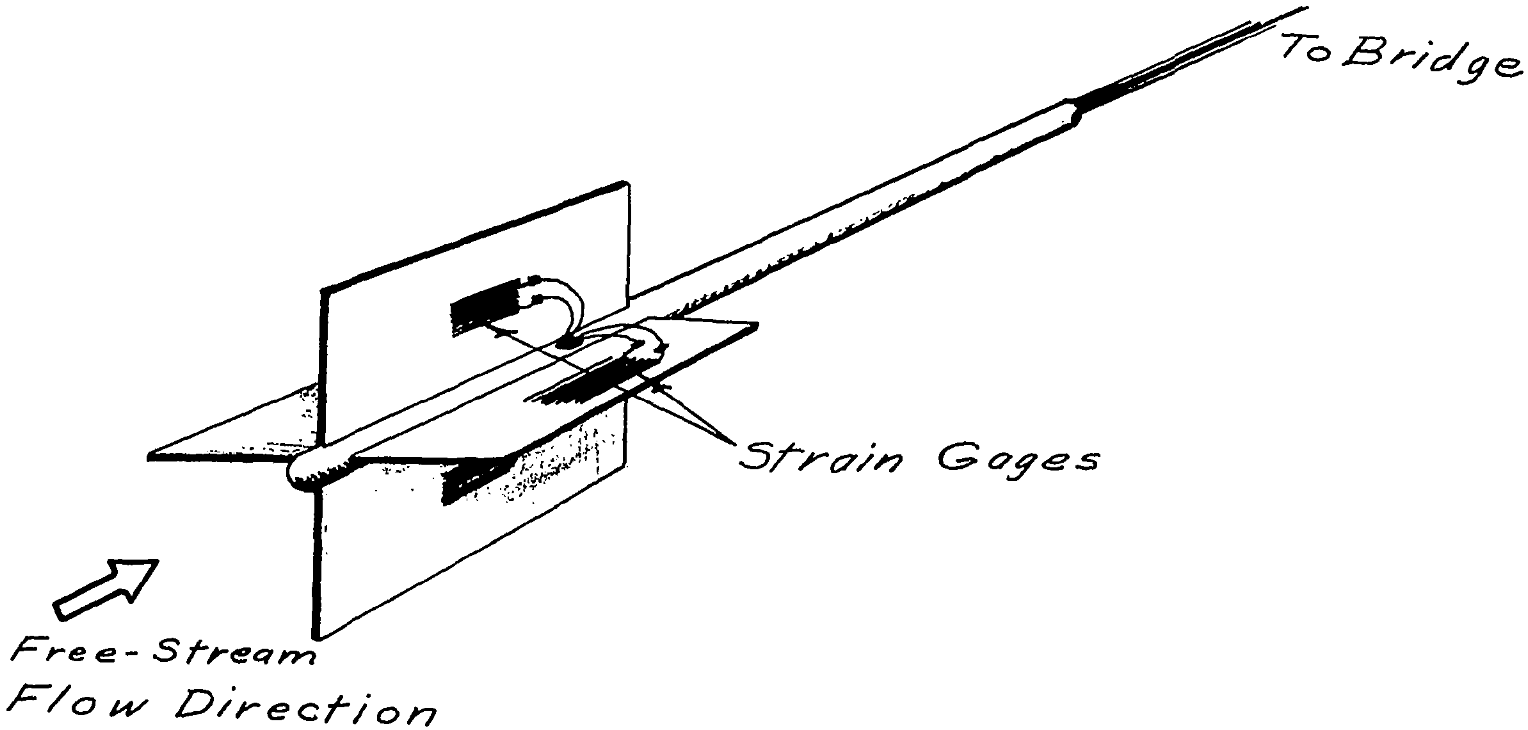


FIGURE 2

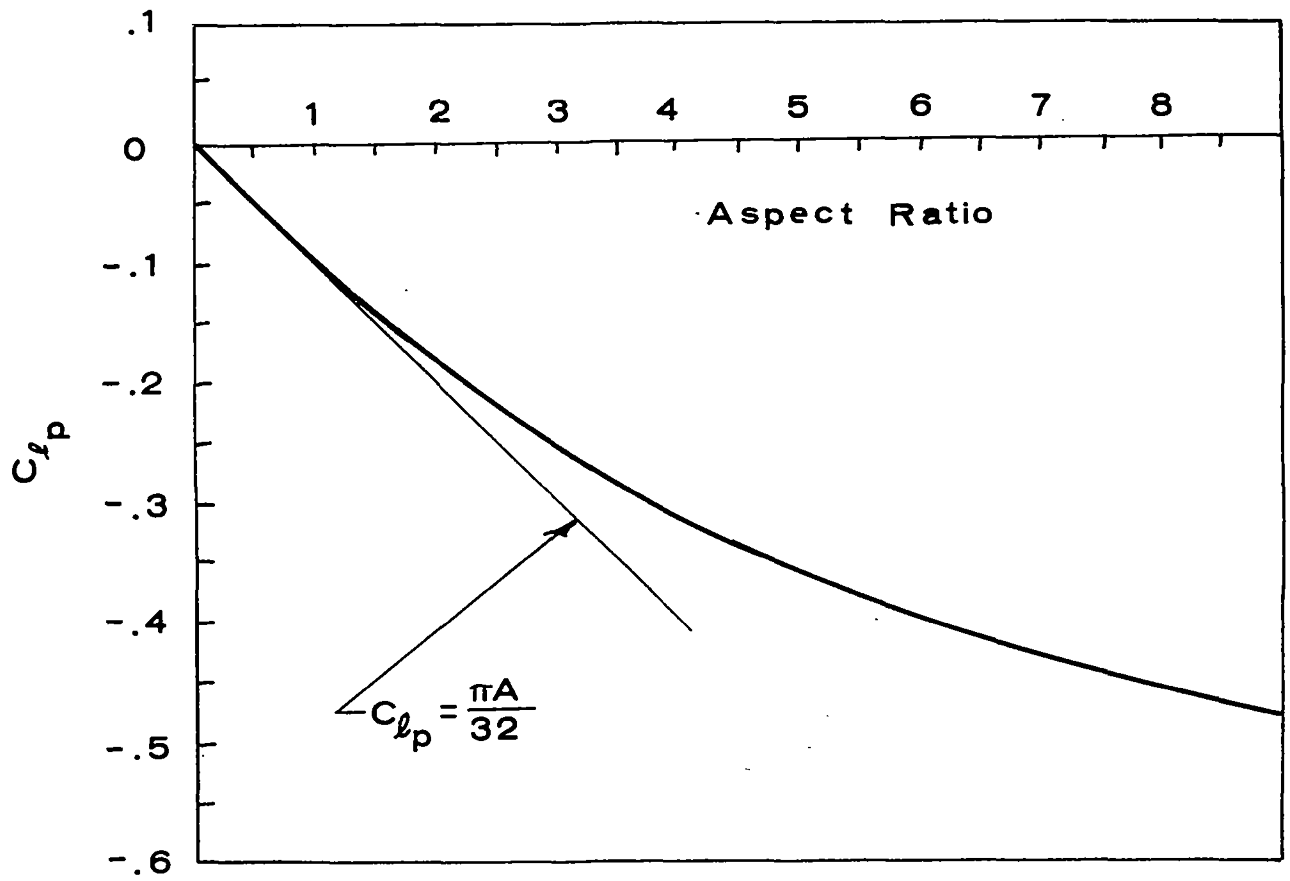


Figure 3. Variation of Damping-in-Roll Parameter with Aspect Ratio at $C_L = 0$.

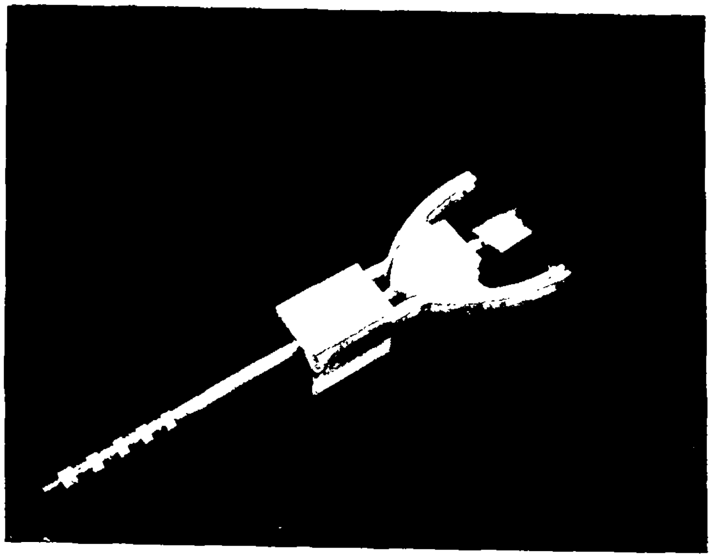
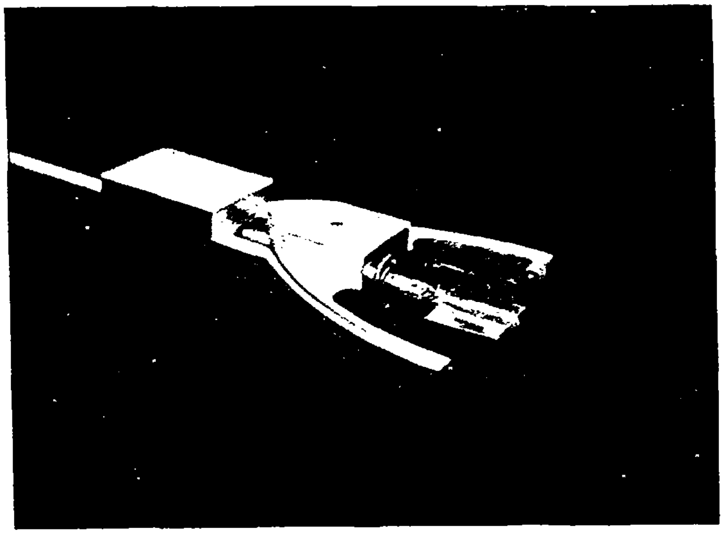
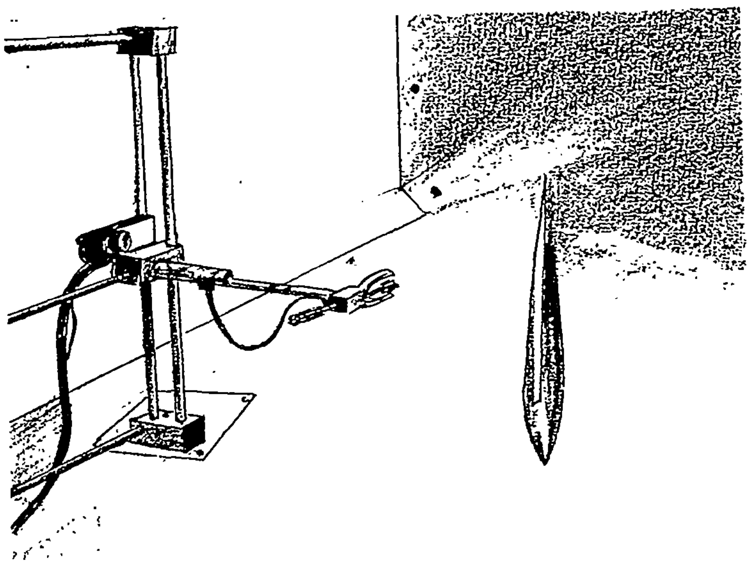


FIGURE 4. Vorticity Probe and Housing

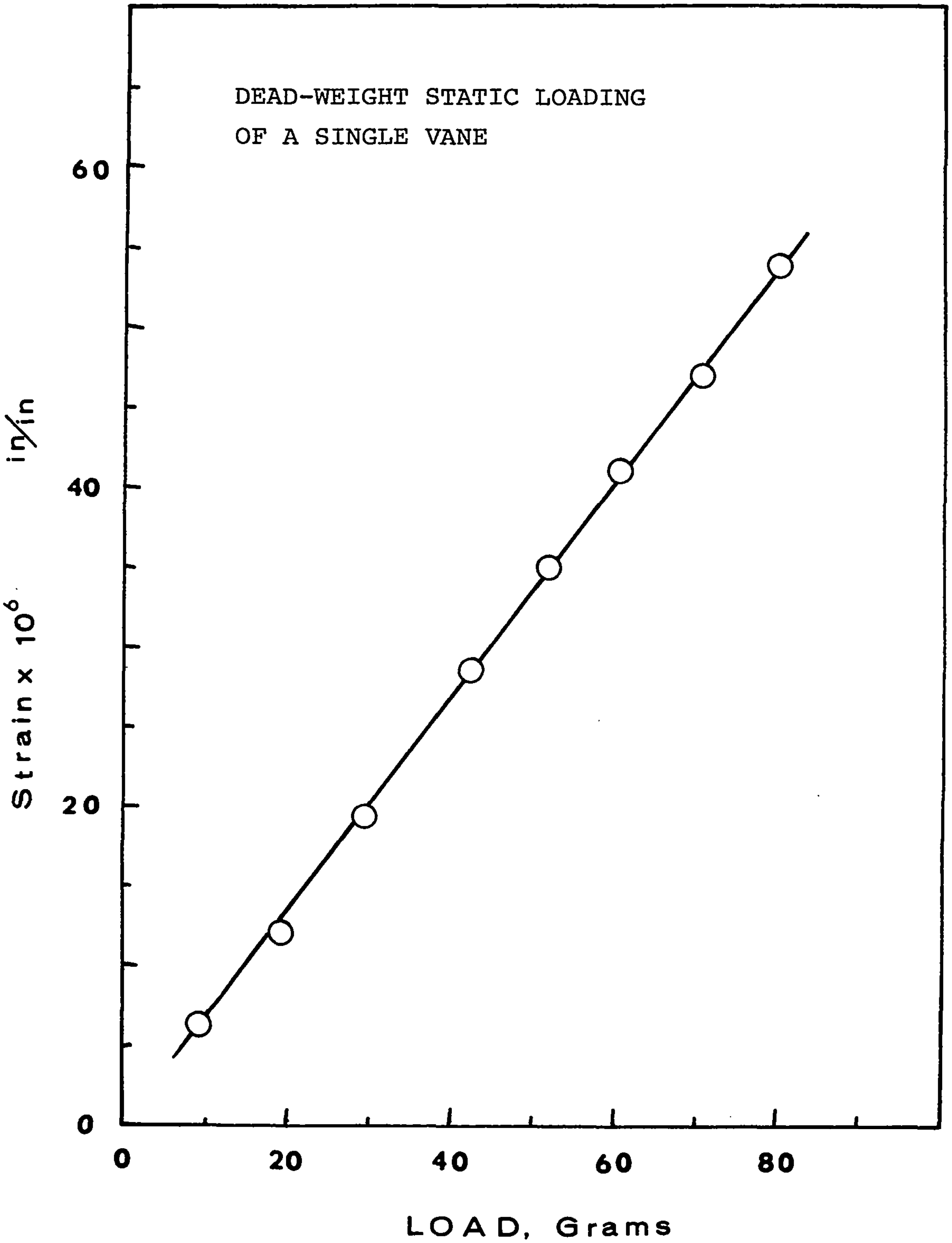


(a)



(b)

FIGURE 5. Vorticity Probe



DEAD-WEIGHT STATIC LOADING
OF A SINGLE VANE
Strain x 10^6 in/in
0
20
40
60
0
20
40
60
80
LOAD, Grams

Figure 6

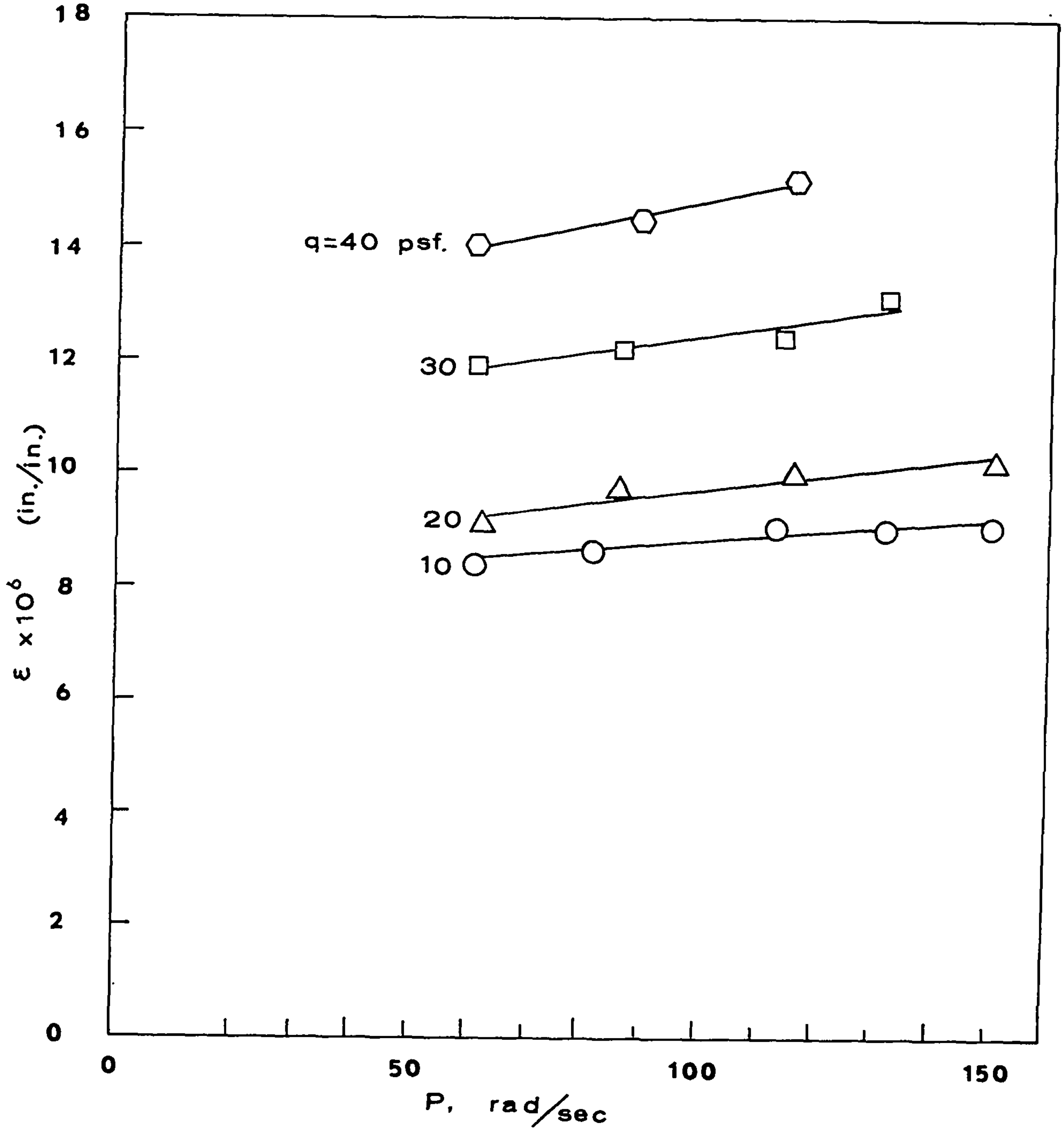


Figure 7. Probe Calibration

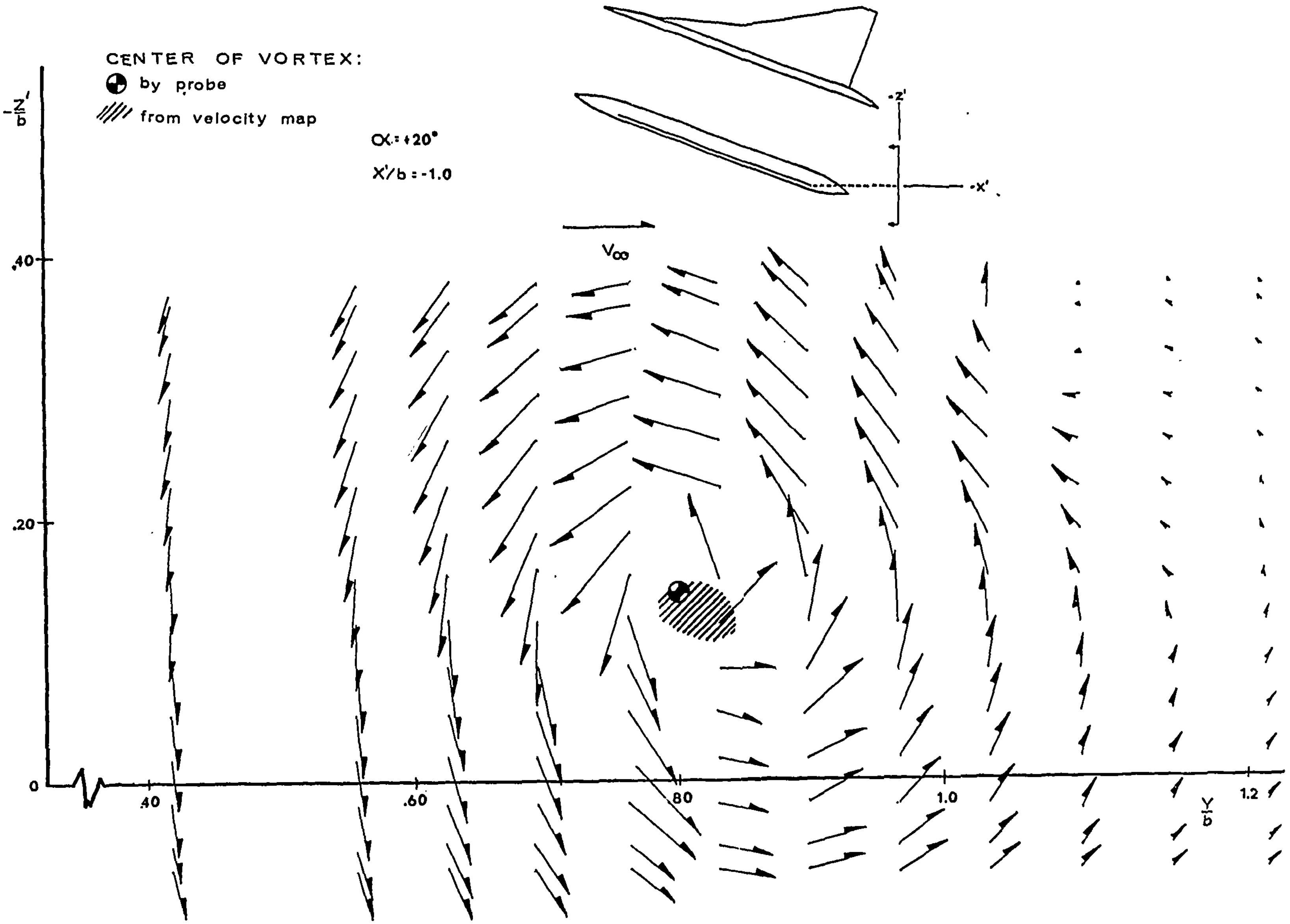


Figure 8. Flow field downstream of wing trailing edge.